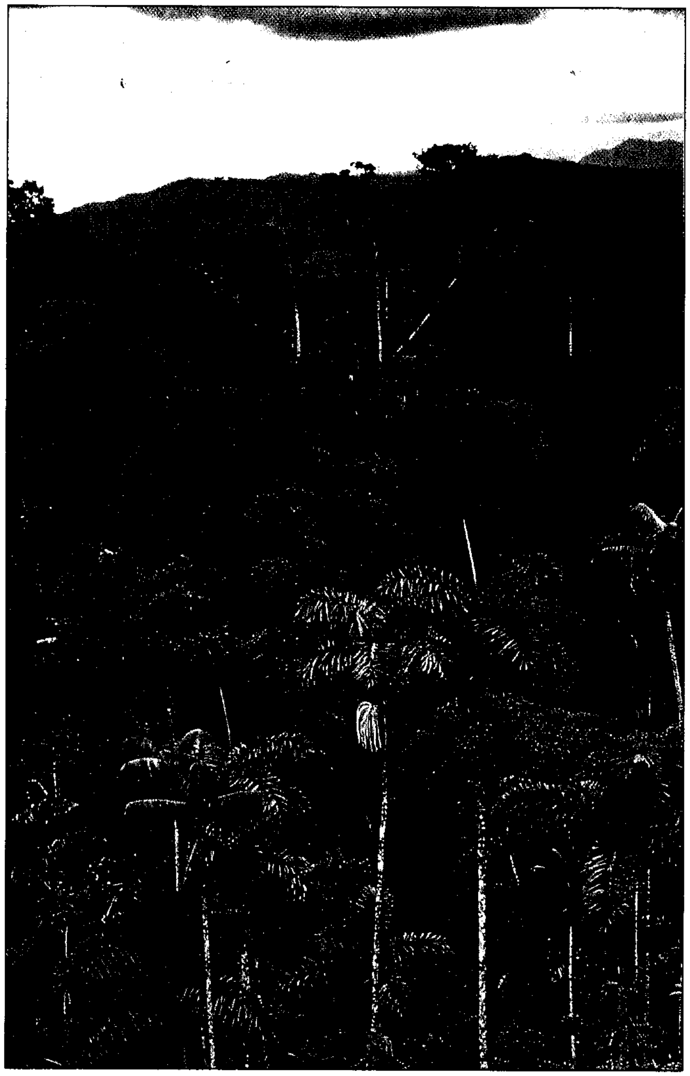
Steven W. Running, Thomas R. Loveland and Lars L. Pierce

A Vegetation Classification Logic Based on Remote Sensing for Use in Global Biogeochemical Models

A simple new classification logic for global vegetation is proposed. The critical features of this classification are that: it is based on simple, observable, unambiguous characteristics of vegetation structure that are important to ecosystem biogeochemistry and can be measured in the field for validation; the structural characteristics can be determined by remote sensing, so that repeatable and efficient global re-classifications of existing vegetation will be possible; and the defined vegetation classes directly translate into the biophysical parameters of interest by global climate and biogeochemical models. A first test of this logic for the continental United States is presented based on an existing 1 km Normalized Difference Vegetation Index database. Currently recognized global biome classes can easily be derived from this classification by adding climate descriptors and defining mixtures of these fundamental six vegetation classes.



The world's plant cover is complex and variable, and much is not readily accessible for direct scientific study.

INTRODUCTION

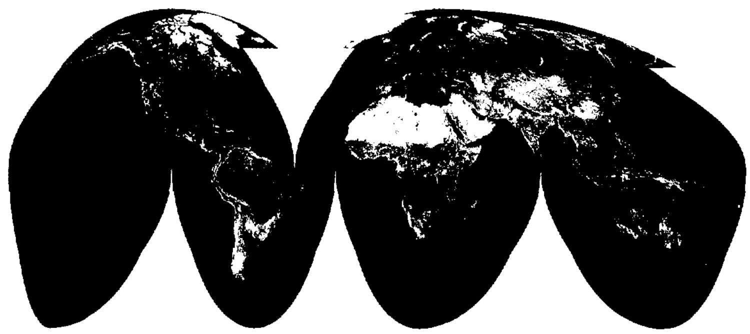
Accurate representation of the terrestrial biosphere in models of the Earth system is a continuing challenge. The range of climates, geomorphic substrates, natural disturbances and human encroachments occurring globally has produced an incredible diversity of terrestrial vegetation. Scientists have been faced with not only developing a logic for simplifying vegetation into a smaller array of critical attributes, but also developing a means of measuring vegetation on a fully global basis. First attempts at developing a global vegetation database illuminated a variety of problems of raw data availability, inconsistency of historical vegetation definitions, and difficulty in translating taxonomic nomenclature to global modeling requirements (1, 2).

Global vegetation databases have been developed from published maps, atlases and national databases that attempt to represent existing vegetation (1). These databases provide global models with a generally realistic estimate of current landcover. However these databases suffer from lack of consistency in vegetation classification used, variable measurement techniques, and a variety of spatial sampling resolutions. Not infrequently, 10 000 km^2 may be sampled and represented by one 1 ha plot, and the possibility of repeating the measurement may be nil.

There is a rich history of bioclimatically derived global vegetation classifications. The best known are by Holdridge and Koppen, recently reviewed by Prentice (3). These schemes use simple temperature and water indices to define potential vegetation types and global distribution. Recently, more mechanistic logics have been derived (4–7) that define the geographic distributions of biomes based on specific physiological tolerances of different plant types to cold tolerance, growing season heat sums, and drought stress. Because climate is an integral part of their classification schemes, a number of classes of equivalent vegetation type, such as forests, are defined separately as boreal/temperate/tropical forest, to provide geographic specificity. Although these new biome models are improving the global classification of vegetation, they produce only maps of *potential*, not existing vegetation.

A very useful evaluation of global change could be done by comparing potential biome maps with existing biome maps. Estimates of the amount of the global land surface perturbed from its original vegetation range between 10–20%, and is increasing annually at unknown rates, a critical factor to monitor in global change research (8). Because there is no clearly defined set of vegetation characteristics used for these classifications, there is significant disagreement among authors of the existing global areal extent of different biome classes.

Consequently, Townshend et al. (8) argued that the most essential new global vegetation classification must be driven by remote sensing, to provide a realistic measure of *existing* land-cover. Use of a consistent, remote-sensing based measurement regime could eliminate the ambiguities currently extant in global vegetation maps derived from varying methodologies and definitions. However, current remote sensing capabilities, unless extensively augmented by ancillary data, cannot consistently produce the large number of land-cover classes usually defined, particularly because climate classes are usually part of the definition (9). We suggest that a simpler logic is needed, based only on observable plant physiognomic characteristics.



International collaboration has made it possible to obtain fully-global information on vegetation characteristics at 1 km resolution, updated every 10 days, using data from the Advanced Very High Resolution Radiometer (AVHRR) sensor.

For global modeling requirements, the development of realistic models of climate, carbon cycles, hydrology, etc., all rely on an unambiguous, repeatable definition of existing land-cover. Each cell of a global model is defined with a certain landcover, and from that definition a number of biophysical parameters are derived for use in the energy and mass flux calculations of the model. Most global climate and biogeochemical models immediately translate the land-cover classes into biophysical parameters, such as leaf area index and roughness length (10–12). The newest general circulation models (GCMs) are planning to define seasonally dynamic land-cover based on vegetation phenology (12), a capability offered by the daily repeat time of the AVHRR sensor (9, 13).

Global carbon cycle models may additionally require some parameterization of leaf or canopy geometry for gas-exchange calculations, such as broadleaf vs needleleaf; canopy longevity, such as deciduous versus evergreen habit, and physiological capacity, such as maximum photosynthetic rate (14). The continued development of global models within the International Geosphere-Biosphere Programme (IGBP) and other internationally-coordinated studies is becoming hindered by the lack of an agreed classification logic from which to begin these model parameterizations.

The objective of this paper is to introduce a new logic for global vegetation classification that could solve a number of the problems stated. The logic is: i) based on simple, observable, unambiguous characteristics of vegetation structure that are important to ecosystem biogeochemistry and could be measured in the field for validation; ii) based on remote sensing, so that repeatable and efficient global re-classifications of existing vegetation will be possible; and iii) directly translatable into the biophysical parameters of interest by the global climate and biogeochemical models, including the ability for some advanced inferences of important vegetation properties that cannot be determined by remote sensing. Important to this logic is the explicit separation of climate from the classification to allow remotely-sensed classes. Temperate, tropical, boreal and other climatic labels can be added later with specific ranges of temperature and precipitation to produce refined sub-classes for comparison with the potential biome classifications of Prentice et al. (5) and Neilson et al. (6, 7).

CLASSIFICATION LOGIC

We suggest that a complete global vegetation classification be derived from combinations of three primary attributes of plant-canopy structure. These attributes are *permanence of aboveground live biomass, leaf longevity*, and *leaf type* (Fig. 1). Possible combinations of these three vegetation attributes yield only six fundamental vegetation classes, although they occur across a range of climates, which we will deal with separately.

The first criterion of the classification, permanence of aboveground life biomass, defines whether the vegetation retains

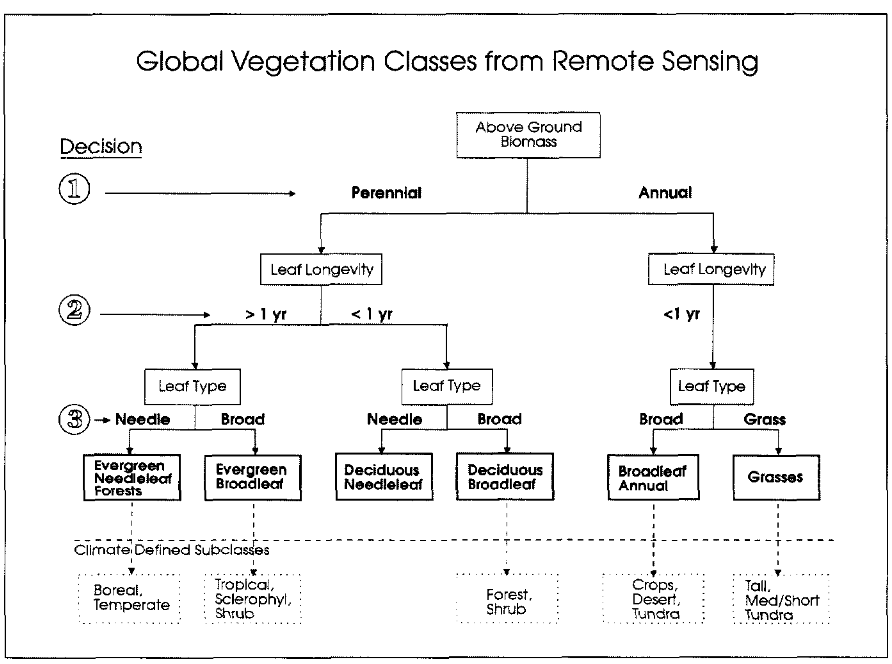


Figure 1. A flowchart of our global vegetation classification logic. Each simple box identifies the variable being defined, and each decision point is illustrated. The final six classes of vegetation are shown in bold. Below the dotted line, potential-climate defined subclasses corresponding to more common classification schemes are suggested.

perennial or annual aboveground biomass, a critical question for seasonal climate and carbon-balance modeling. This class separates vegetation with permanent respiring biomass (forests and woody stemmed shrubs) from annual crops and grasses that go through non-growing season periods as seed or belowground structures only. It also is the major vegetation determinant of the surface roughness/length parameter that climate models require for energy and momentum transfer equations. This distinction merely requires that remote sensing is able to detect the presence or absence of aboveground biomass during the non-growing season.

The next step of the classification, leaf longevity, or often termed evergreen versus deciduous canopy, is an extremely critical variable in carbon-cycle dynamics of vegetation, and is important for seasonal albedo and energy transfer characteristics of the land surface. This leaf longevity class defines whether a plant must completely regrow its canopy each year, or merely a portion of it, with inferred consequences to carbon partitioning, leaf litterfall dynamics and soil carbon. To make the class discrimination simple enough to be remotely sensed and for compatibility with existing vegetation schemes, we define only leaf longevities of less than or greater than one growing season, effectively evergreen versus deciduous. We recognize that leaf longevity of evergreen trees can range as high as 20 years, but we see no possibility of remotely sensing this characteristic, and the ecological significance is greatest distinguishing simple deciduous versus evergreen status. Most needleleaved biome types are evergreen, the exception being the deciduous conifer *Larix*, or larch forests of temperate and boreal regions. Most grasses are deciduous, but this criterion separates evergreen broadleaved forests and shrublands from deciduous forests, annual crops and climate dependent annual vegetation such as desert and tundra.

The third classification criterion is simple leaf type or shape. Based on both the spectral/optical properties of leaves and their gas-exchange characteristics, we feel only three leaf types need to be defined: needleleaved, broadleaved, and grasses. The needle-leaved and grass classes are fairly straightforward representations of those vegetation types. However, the broadleaf class includes trees, shrubs, herbs and crops that fit this leaf type criterion. Hence, the third criterion requires the solution of the first two criteria (perennial, and evergreen/deciduous) to provide meaningful discrimination of vegetation.

After this three step classification, climate descriptors can be included from a variety of sources. Annual or monthly global climate data can be used to derive sub-classes like tropical/temperate/boreal from either classic Holdridge or Koppen type schemes (3), or newer rule-based bioclimate models (5–7). The difference between previous classifications and ours is that we have *defined specific vegetation attributes that are remotely sensible, and climate is independently added so as to simplify the classification logic.*

AVHRR-BASED IMPLEMENTATION

We feel that this logic can be implemented with fair accuracy by the current satellite systems, with the procedures described below. Virtually all current remote-sensing-based global vegetation analysis is done with the daily polar orbiting Advanced Very High Resolution Radiometer, AVHRR. The well-known Normalized Difference Vegetation Index (NDVI) is the most commonly used measure of vegetation, and a long literature of studies exists on NDVI (9, 15–17). The strength of global NDVI data is the high temporal information content. The common compositing time of 10–14 days provides 25–30 NDVI datasets per year. Thus, beyond the absolute NDVI value, the seasonal trajectory of the NDVI can define important attributes of vegetation phenology (Fig. 2).

The most direct distinction of perennial versus annual vegetation is the presence or absence of live aboveground biomass in the nongrowing season. Two approaches are used to distinguish vegetated from nonvegetated land in the nongrowing season. One is a nongrowing season minimum NDVI threshold, 0.1 was used in Loveland et al (9), below which the pixel is considered non-vegetated. However, while this strategy can be used reliably on a regional basis, asynchronous growing seasons (e.g. winter for Mediterranean climates, summer for temperate, rain triggered in deserts) make this simple approach more difficult for global studies. The second logic evaluates the time period of NDVI above a threshold, a greenness duration, given in days. A longer greenness duration implies perennial biomass.

There are two particular difficulties in the remote sensing of non growing season biomass. First, solar illumination angles, and incident radiant energy are low, especially at high latitudes. Second, distinction can be difficult between dead biomass, or aboveground litter (such as dead grasses), and the live biomass of interest. Two alternative remote-sensing strategies to NDVI

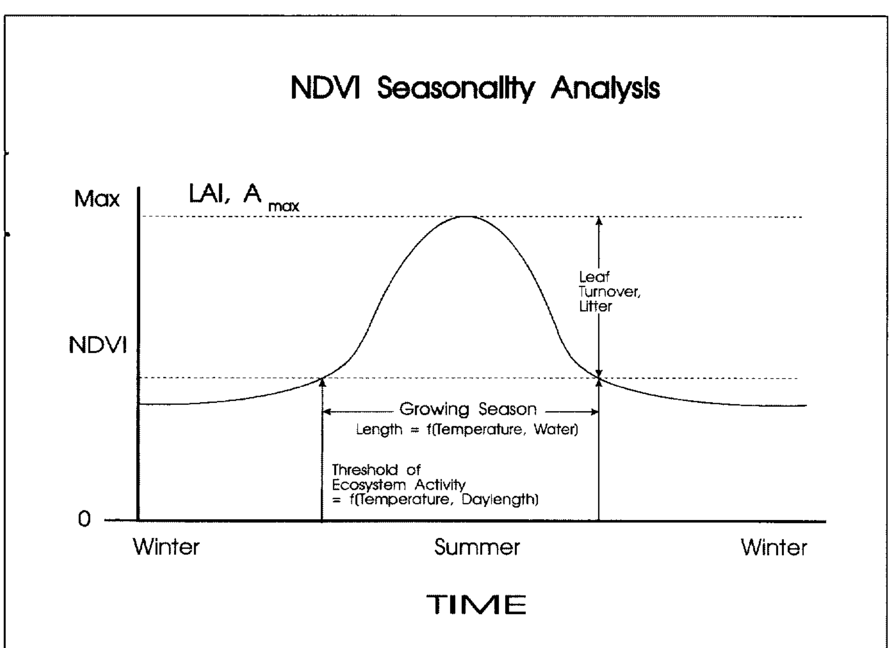


Figure 2. A conceptual diagram of how the seasonal trace of Normalized Difference Vegetation Index (NDVI) data may be used to distinguish perennial from annual aboveground biomass types, based on minimum thresholds, and leaf longevity, or evergreen from deciduous classes, based on NDVI amplitude.

analysis alone are being considered. Although the NDVI is higher over vegetated than nonvegetated areas regardless of the presence of green leaf area, the best discrimination may be done with single channel 1 data alone, of shortwave reflectance. In seasonally snow covered areas, permanent vegetation often stands above the ground-snow cover, while areas of annual vegetation show a purely snow-covered surface. Addition of surface temperature from the AVHRR thermal channels 4 and 5 has improved biome type discrimination. Nonvegetated surfaces have much higher surface temperatures when fully illuminated than vegetated surfaces, so surface temperature extremes can identify nonvegetated areas (18). We are continuuing to explore the optimum remote-sensing analysis for answering this first classification criterion efficiently and unambiguously.

The second decision in the hierarchy of Figure 1 is discrimination of deciduous from evergreen vegetation, or leaf longevity. This decision is already partly answered in decision 1: annual vegetation is always deciduous. The seasonal amplitude of NDVI, the difference between the lowest NDVI before spring leaf growth, and the peak mid-summer NDVI usually provides a clear distinction between evergreen and deciduous vegetation (9) (Fig. 2). Evergreen vegetation retains a much higher year around NDVI due to continuous foliage, so the NDVI amplitude is much smaller (19).

The final decision, and third criterion, distinguishes needleleaf versus broadleaf versus grass, three fundamental leaf types with highly contrasting energy transfer and ecological characteristics. This discrimination is the most difficult, from current remote sensing, and may involve differentiating the bidirectional reflectance distribution function (BRDF) of these leaf and implicitly, canopy types. Vegetation canopies are not isotropic: their reflectance and shadowing changes directionally with illumination and view angles. Simple categorization of these leaf types may be possible with directional remote-sensing data.

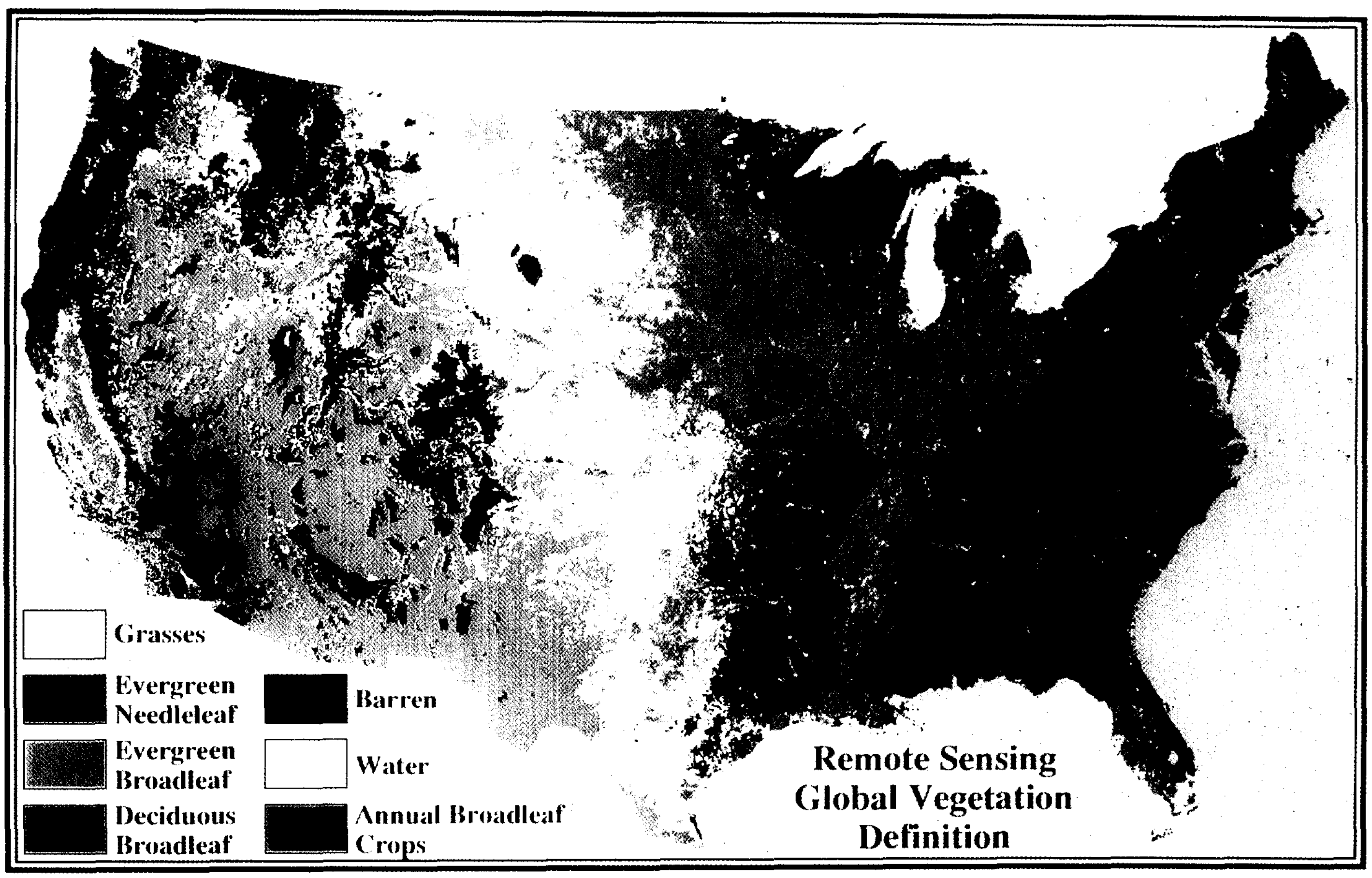
However, nadir-viewing AVHRR data also produces variable reflectances. The two extreme classes, evergreen needleleaf forest and grasses may often be fairly readily distinguished, the evergreen forests always have very low reflectance resulting from the narrow leaf geometry and diffuse canopy structure. If the initial decisions, and discriminations are done correctly, this final decision is much more tractable. Evergreen needleleaf forests and evergreen broadleaf forests rarely intermix geographically, so if necessary could be separated by simple climate zones. The deciduous needleleaf tree *Larix* intermixes with evergreen needleleaf forests in temperate regions of North America and Asia.

A variety of vegetation types fall into the broadleaf annual class, including most crops, and many desert and tundra types in climates too harsh to sustain perennial plant life. For purposes of biophysical parameterization, these plant types can all be defined together, so form the final class of this remote-sensing based logic. However, when finer discrimination is required, the climatic subclassification easily separates agricultural crops from drought-limited deserts, and temperature-limited tundra. Even without explicit climate definition the time integration of NDVI, or the simple growing season duration in days defined by NDVI seasonality discriminates these classes (9).

A FIRST CLASSIFICATION TEST

The final vegetation classification describes six different basic classes or lifeforms of global vegetation. A first test of this logic, for the United States, where 1 km AVHRR data were already available, is shown in Figure 3. In this exercise, the 159 seasonal land-cover regions originally defined in Loveland et al. (9) were translated into the three attribute criteria and then combined into the six classes defined in Figure 1.

Figure 3. A map of the six proposed vegetation classes for the conterminous United States derived from the land classification database of Loveland et al. (9).



There were clear advantages to mapping vegetation based on the logic in Figure 1, compared to the original classification of Loveland et al. (9). In the original classification, almost 85% (60 of 71) of the preliminary regions defined by initial spectral-temporal clustering algorithms of the NDVI data, contained multiple land-cover types that required use of elevation, climate and eco-region variables to eliminate confusion. However, when translating the original 71 classes to the logic in Figure 1, only 28% contained unacceptable attribute conflicts. The emphasis on structural aspects of vegetation rather than floristic or taxonomic elements clarifies the spectral and temporal classification process.

In all cases, confusion points involved the separation of land into perennial versus annual above-ground biomass when annual irrigated broadleaf crops shared a similar NDVI temporal profile with high elevation evergreen needleleaf forests in the western US. The NDVI signal in these forests was reduced during the autumn, winter and spring due to snowcover, while the harvested crops were also reduced in NDVI. In the spring, the melting of snow produced a perceived 'onset of greenness' nearly identical to the germination of these row crops. However, this confusion could easily be eliminated with ancillary elevation data. Digital topographic data is an important ancillary database in global research that is already available at varying resolutions for each continent (20).

Interpretation of the other attributes, leaf longevity and leaf type, appear straightforward, and can be interpreted based solely on remote-sensing data. Even with the confusion associated with the identification of aboveground biomass, the reliance on ancillary data is significantly reduced, and the ability to efficiently and consistently identify the six landcover classes is much higher than with the more complicated floristic logic of Loveland et al. (9).

FUTURE WORK

Advanced remote-sensing capabilities need to be explored, specifically for defining the third criterion of Figure 1, the needleleaf versus broadleaf versus grass distinction. We feel the greatest promise will be from directional remote sensing, such as the advanced solid-state array and multi-angle imaging spectroradiometers (ASAS and MISR; 21, 22). When the Earth Observing System is operational in 1998, the Moderate Resolution Imaging Spectrometer (MODIS) with 36 spectral channels and daily global coverage will allow a number of advanced vegetation indices that will substantially improve on the vegetation discrimination now possible with the 2 channel NDVI (23). Translation of the simple vegetation classes in this classification into advanced biophysical parameters will allow implemention with advanced global biogeochemical models (24). Climate subclasses need to be added whenever translation of this classification into current global biome classes is required. Also, some global biomes may best be described as a mixture of these six simple classes. For example, many savanna types can be described as a mix of evergreen needleleaf or evergreen broadleaf forest with a grass ground cover. Remote sensing of these mixtures can present challenging, mixed-pixel problems, but certain clearly defined mixtures may provide an easy enhancement to these first simple logical classes. Finally, as the first complete 1 km AVHRR dataset becomes available in 1994, a global implementation of this classification scheme is planned.

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